Journal of Arid Environments 55 (2003) 737–746

Journal of Arid Environments

www.elsevier.com/locate/jnlabr/yjare

Variability in soil redistribution in the northern Chihuahuan Desert based on ^{137}Cesium measurements

Jerry C. Ritchie[a,*], Jeffrey E. Herrick[b], Carole A. Ritchie[c]

[a] *USDA ARS, Hydrology and Remote Sensing Laboratory, Building 007, Room 104 BARC-West, Beltsville, MD 20705, USA*

[b] *USDA ARS Jornada Experimental Range, Las Cruces, NM 88003, USA*

[c] *Botanical Consultant, Laurel, MD 20708, USA*

Received 24 June 2002; accepted 30 October 2002

Abstract

A hypothesis for understanding the stability of northern Chihuahuan Desert landscapes is that the distribution of soil resources changes from spatially homogeneous in arid grasslands to spatially heterogeneous in invading shrublands. Since radioactive fallout ^{137}Cesium (^{137}Cs) was deposited uniformly across the landscape during the 1950s and 1960s and was quickly adsorbed to soil particles, any redistribution of ^{137}Cs across the landscape would be due to soil redistribution or instability at either plant-interspaces or on a landscape scale. The concentration of ^{137}Cs in soils collected from different vegetation communities (black grama grass, tarbush, tobosa grass, and mesquite) at the USDA-ARS Jornada Experimental Range in the Northern Chihuahuan Desert in New Mexico was determined. At the black grama grass and tobosa grass sites, ^{137}Cs was uniformly distributed at the plant interspace scale. At the mesquite sites, ^{137}Cs was concentrated in the dune area under mesquite shrubs with little to no ^{137}Cs in the interdune areas. ^{137}Cs data support the hypothesis that significant soil redistribution has occurred at dune sites created by invading mesquite. In the arid grassland-shrub sites with black grama grass, tobosa grass, and tarbush the ^{137}Cs data support the hypothesis of spatially homogeneous distribution of soil resources. High concentrations of ^{137}Cs in the biological soil crusts (0–5 mm) at the tarbush sites indicate that biological soil crusts can contribute to the stability of these sites.
Published by Elsevier Science Ltd.

Keywords: Cesium-137; Chihuahuan desert; Soil redistribution; Mesquite; Grassland

*Corresponding author. Tel.: +1-301-504-8717; fax: +1-301-504-8931.

0140-1963/02/$ - see front matter Published by Elsevier Science Ltd.
doi:10.1016/S0140-1963(02)00315-4

1. Introduction

Large areas of arid grasslands of the northern Chihuahuan Desert have been replaced by shrub communities in the last century. These changes have been linked to climate, grazing, and human impacts (Buffington and Herbel, 1965; Gibbens et al., 1992; Havstad and Schlesinger, 1996). A conceptual model (Wright and Honea, 1986; Schlesinger et al., 1990, 1996) hypothesizes that grasslands have uniform distribution of water, nutrients, and soil resources while shrublands increase the spatial and temporal heterogeneity of these resources. The stability of these systems can be defined as the capability of a site to limit redistribution and loss of soil resources (including nutrients and organic matter) by wind and water.

Radioactive ^{137}Cesium (^{137}Cs) was globally distributed by the deposition of fallout from atmospheric nuclear weapon tests in the 1950s and 1960s mostly by rainfall (Playford et al., 1993; Cambray et al., 1989; Carter and Moghissi, 1977). While rainfall may be patchy in arid landscapes, the assumption is that over the 30-year period of radioactive fallout all areas would have approximately uniform rain and fallout deposition. Once ^{137}Cs reached the soil surface it is strongly and quickly adsorbed on the exchange sites of the soil particles and is essentially nonexchangeable in most environments (Tamura, 1964; Cremers et al., 1988). Chemical and biological processes move little ^{137}Cs once it reaches the soil surface except where there is significant animal activity (e.g. badger borrows, kangroo rat mounds), thus physical processes of water and wind erosion are usually the dominant factors moving ^{137}Cs-tagged soil particles between and within landscape compartments (Ritchie and McHenry, 1990).

Our hypothesis is that ^{137}Cs concentrations in the soil will change from uniform distribution to a more heterogenous distribution at both plant-interspace and landscape scale in the Jornada basin as the soil is redistributed under the different vegetation communities. The purpose of this study was to use the distribution of ^{137}Cs in the soil of different vegetation communities at the USDA-ARS Jornada Experimental Range in New Mexico as an indicator of soil redistribution at different scales.

2. Study area

The USDA ARS Jornada Experimental Range (783 km^2) and the adjacent New Mexico State University Chihuahuan Desert Rangeland Research Center (NMSU–CDRRC, approx. 250 km^2) lie 40 km northeast of Las Cruces, New Mexico on the southern end of the Jornada del Muerto Plain. The Jornada basin is part of the larger Jornada del Muerto Basin and is typical of the Basin and Range physiographic province of the American Southwest and the northern part of the Chihuahuan Desert (MacMahon and Wagner, 1985).

The Chihuahuan Desert is the most arid of the North American grasslands. The vegetation is characteristic of a subtropical ecosystem in the hot desert biome. The grasses, primarily C4, include black grama [*Bouteloua eriopoda* (Torr.) Torr.], mesa dropseed [*Sporobolus flexuosus* (Thurb. Ex Vasey) Rydb.], and three awn [*Aristida ternipes Cav*. and *Aristida pansa* Wooton & Standl.] growing on course-textured soils and tobosa grass [*Pleuraphis mutica* Buckley] and burrograss [*Scleropogon brevifolius* Phil.] in soils with more silts and clays. Shrubs and suffrutescents include honey mesquite [*Prosopis glandulosa* Torr.], four-wing saltbush [*Atriplex canescens* (Pursh) Nutt.], creosote bush [*Larrea tridentata* (Sesse & Moc. ex DC.) Coville], tarbush [*Flourensia cernua* DC.], broom snakeweed [*Gutierrezia sarothrae* (Pursh) Britton & Rusby], and soaptree yucca [*Yucca elata* (Engelm.) Engelm.]. Seasonal rains trigger flushes of both annual and perennial forbs such as spectaclepod [*Dithyrea wislizenii* Engelm.], desert baileya [*Baileya multiradiata* Harv. & Gray], and leatherweed croton [*Croton pottsii* (Klotzsch) Muell.Arg.]. Although a few species dominate (Gibbens, R. McNeely and B. Nolen, Jornada Vegetation Map, unpublished), more than 490 plant species have been identified on the Jornada Experimental Range.

Black grama and tobosa grass communities, which once dominated the landscape have been susceptible to encroachment by shrubs during the last century. A land survey of 1858 and vegetation surveys made in 1915, 1928, and 1963 show that total area dominated by grass had decreased from 90% in 1858 to 23% in 1963 (Buffington and Herbel, 1965). Droughts, grazing by livestock and native fauna, and shrub seed dispersals by livestock have all contributed to the spread of shrub (Grover and Musick, 1990; Havstad and Schlesinger, 1996). Conversion from grass- to shrub-dominated plant communities on deep coarse-textured soils characteristically resulted in the formation of coppice dunes (Buffington and Herbel, 1965), increasing spatial heterogeneity of critically limiting nutrients (especially N) required for plant growth (Schlesinger and Pilmanis, 1998), and increasing wind erosion (Gibbens et al., 1983). On fine-textured soils, shrub invasions have resulted in reduced infiltration and increased runoff.

3. Sample sites

3.1. Black grama grass site

Areas typical of the black grama grass communities were sampled inside the Mayfield Well Exclosure on the NMSU-CDRRC (Fig. 1). This exclosure is dominated by black grama with no livestock grazing for 60 years. Black grama grass patches which have not been invaded by shrubs persist in this exclosure. We used soil samples from these patches as the reference sites for the total input of ^{137}Cs to the area and for estimating erosion rates.

3.2. Tobosa grass site

Areas typical of tobosa grass community were sampled inside and outside the Tobosa Clipping Exclosure (Stewart Rain Gauge) on the Jornada Experimental Range (Fig. 1). Samples were collected inside the exclosure along a line 1 m south of the north edge of exclosure, 3, 8, and 13 m east of the west edge of the exclosure.

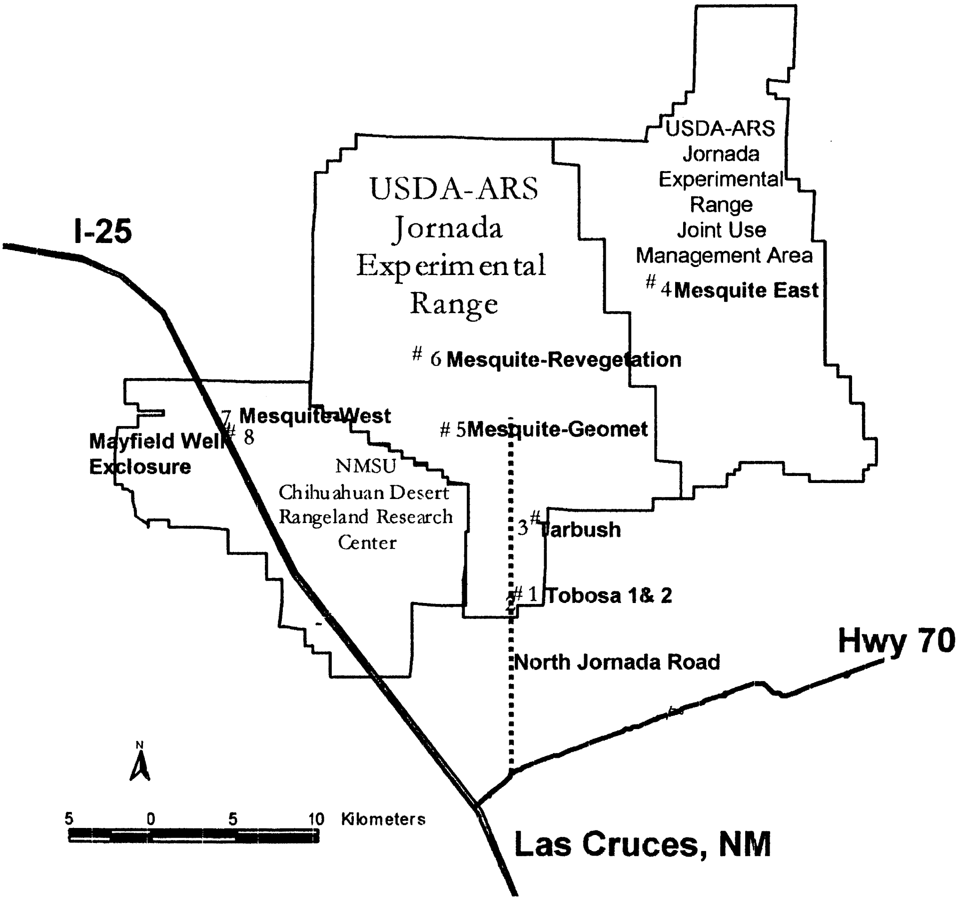

Fig. 1. Map of the USDA ARS Jornada Experimental Range and the NMSU Chihuahuan Desert Rangeland Research Center showing the location of the sample sites.

Vegetation is nearly 100% tobosa grass and canopy cover is estimated to be greater than 80% inside the exclosure. Samples outside the Tobosa Clipping Exclosure were collected along a line 20 m north of the north edge of exclosure. Vegetation along this line is also nearly 100% tobosa grass, and canopy cover is estimated to be greater than 70% in the area. Some surface disturbance of the soil was visible from old prairie dog holes. All prairie dogs were exterminated from this site prior to 1940.

3.3. *Tarbush site*

An area typical of tarbush communities was sampled at the Tarbush long-term surface disturbance experimental exclosure. Soil samples were collected 1 m inside the east fence line. Soil biological crust samples (0–0.5 cm depth) were collected where highest cover of noncollema (i.e. later successional) lichens were found.

3.4. Mesquite sites

Soils from mesquite dune vegetation type were collected on an east–west transect across the Jornada Basin at four locations: east side of the Jornada Experimental Range, Geomet site, natural revegetation site, and the Mayfield Well area on the west of the Jornada Basin. At the dune sites soil samples were collected from the middle of the dune and from the interspace between dunes.

The East Side Dune Area is located on lower alluvial fans on the west side of the San Andres mountains, where eolian material has been deposited on top of the alluvial material. Two dune areas were sampled. The first area was in a slight depression where evidence of ponding was found in interspaces. Soils are red loamy sand to 10 cm, then gray silt loam to stage III calcic at >50 cm (Gile et al., 1966, 1981). The vegetation is a mix of mesquite, creosote bush, and tarbush with few grasses and forbs in the interspaces between the dunes. The second east side dune site was approximately one kilometer west of the first site. Soils are red loamy sand to 7–8 cm, then gray silt loam to stage II calcic at 40 cm. The vegetation is a mix of mesquite, creosote bush and tarbush. Interdune soils were sampled from those areas that appeared to have the highest cyanobacteria crust biomass. High cyanobacteria crust biomass is generally associated with less recent disturbance and higher silt content (Belnap and Lange, 2001).

The Geomet Site is adjacent to a long-term vegetation and soil movement transect established in 1936 perpendicular to what was then a grass-shrub ecotone. The samples were collected from an area located approximately 50 m west of the original ecotone in what was black grama grassland in 1936 (Hennessey et al., 1983). By the 1950s mesquite had begun to invade the site. By 1999, it was dominated by low mesquite coppice dunes. We hypothesize that most of the soil movement at this site should have occurred since 1950. Surface texture at the site is loamy sand, which is underlain by a petrocalcic horizon.

The Natural Revegetation Site (Hennessy et al., 1983) is a 249 ha exclosure established in 1933 to determine if protection from grazing would allow the re-establishment of grass in an area that has recently been colonized by mesquite. The relatively deep, loamy sands of this area have been mapped as thermic Typic Haplargids of the Onite series. Soils of the mesquite dunes are thermic Typic Torripsamments of the Pintura series (Bullock and Neher, 1980). Mesquite maintained its dominance in the area and black grama had completely disappeared by 1980 (Hennessey et al., 1983).

The Mayfield Well Mesquite Dune Area is on the western edge of the NMSU-CDRRC along the original Camino Real, a 400-year-old road connecting Santa Fe and Mexico City, which is now just a two-track dirt road. The dunes showed evidence of erosion with soil height below the stems. Three dunes and interpaces between dunes were sampled.

4. Materials and methods

Our objective was to quantify the total ^{137}Cs in the soil profile so soil-sampling depth was at least 30 cm at each site which was sufficient to collect all of the ^{137}Cs. Soil samples were collected in 1999 at the Geomet, Natural Revegetation, and Mayfield Well Exclosure sites. At these sites small pits were dug and composite samples were collected from A–C horizons. Supplementary samples were collected for 0–10, 10–20, > 20 cm or for a composite 0–30 layer at the same time by driving a 4.5 cm diameter metal tube into the soil to a depth of 30 cm. Five soil cores from each of the three sampling locations were collected and composited into a single sample for analyses. At least three composite samples were collected at each site.

In 2000, soils were sampled at the East Dune, Tobosa grass, Tarbush, and Mayfield Well Dune sites. All samples were collected using the 4.5 cm diameter metal tube. Samples were collected for 0–10, 10–20, > 20 cm or for a composite 0–30 layer. Again five soil cores from each of three sampling locations were collected and composited into a single sample for analyses.

Samples were allowed to air-dry and then passed through a 2 mm screen. Coarse fragments and calcium carbonate nodules larger than 2 mm were not included in the analyses. Coarse materials accounted for less than 10% of the soil volume for all but one of the samples, which contained 13% coarse fragments. Samples were then dried at 80°C for 48 h. One-liter Marinelli Beakers were filled with approximately 1000 g of the dry sieved soils and sealed for gamma ray analyses. Gamma-ray analyses were made with a Canberra[1] Genie-2000 Spectroscopy System with Windows-based software/hardware packages that receives input into three 8192 channel analysers from Canberra high-purity coaxial germanium crystals (HpC > 30% efficiency). The system is calibrated and efficiency determined using an Analytic[1] mixed radionuclide standard (10 nuclides) whose calibration can be traced to US National Institute of Standards and Technology. ^{137}Cs is detected at 662 keV and counting time for each sample provides a measurement precision of $\pm$4–6% for the samples. Estimates of radionuclide concentrations of the samples are made using Canberra Genie-2000 software. ^{137}Cs concentration is expressed in Becquerels per gram (Bq g^{-1}) and converted to Becquerels per square meter (Bq m^{-2}) using bulk density.

Estimates of soil erosion/deposition for each sample site were made using the ^{137}Cs profile distribution model (Walling and He, 1999, 2001). The profile distribution model was developed to calculate erosion or deposition rates for an undisturbed soil profile (undisturbed being defined as not cultivated) based on a comparison of ^{137}Cs in a soil at a reference site and ^{137}Cs in a soil at the sample site. The black grama grass site in the Mayfield Well Exclosure was used as the reference site

[1] Trade names are included for the benefit of the reader and do not imply an endorsement of or a preference for the product listed by the US Department of Agriculture.

5. Results

^{137}Cs concentrations ranged from 0 to 5333 Bq m^{-2} for the 49 sampled soils with an average of 1184 Bq m^{-2}. This range of ^{137}Cs concentrations indicated a great amount of soil movement across the landscape. Table 1 provides a summary of the data for the different vegetation communities sampled.

The Mayfield Well Exclosure grass patch site appears to have been very stable over the past 50 years with the measured concentration of ^{137}Cs of 1112 Bq m^{-2} (Table 1) which is similar to the amount (1100 Bq m^{-2}) of ^{137}Cs estimated to have been deposited in the Jornada Experimental Range area (Walling and He, 2001). It is clear that there was movement of soil particles into and out of the black grama grass site by wind but there appears to be no net change in the ^{137}Cs concentration in the grass patches sampled in the area. This is based on the fact that the coefficient of variation of 34% is similar to values that have been measured at other locations where soils were considered to be undisturbed by erosion (Wallbrink et al., 1994; Sutherland, 1996).

The Tobosa grass sites have uniform distribution of ^{137}Cs and are sites for the influx of ^{137}Cs and thus a net influx of soil material. The coefficient of variation is low especially in the soils collected outside the Tobosa grass exclosure. These sites are in areas of both eolian and alluvial deposition of material. Deposition at these sites is estimated to be greater than 5 t ha^{-1} year^{-1} based on the Profile Model.

The Tarbush site is highly variable with ^{137}Cs concentration of 0.0, 745, and 4667 Bq m^{-2} for the three soil profiles collected. These profiles were less than 50 m apart and all were collected under a Tarbush canopy. The soil with the highest concentration of ^{137}Cs also had the highest estimated cover of noncollema lichens in a soil crust. A sampling of the soil crust (top 5 mm of the soil profile) at two nearby sites gave ^{137}Cs concentrations of 44 and 39 Bq g^{-1} which is twice the ^{137}Cs concentration measured in any other soil samples collected for this study. It is possible that the high ^{137}Cs concentration (4667 Bq m^{-2}) is in part due to the higher cover of noncollema lichens contributing to a higher stability at the site. Studies have shown that lichens tend to concentrate radioactivity (Ritchie et al., 1971). Water flow patterns in the area appear to be similar, but it is possible that the soil profile with no ^{137}Cs was in a flow path of runoff water, which has moved the ^{137}Cs to other locations. Although slopes are extremely low at this site, the soils are highly erodible (both wind and water) when disturbed and runoff rates are extremely high (Herrick et al., unpubl. data). Water-eroded sediment reaccumulate in small depressions created by livestock trampling, while wind-eroded sediment is lost from the site. It is impossible to estimate average erosion at the site since the ^{137}Cs method for measuring erosion requires that at least some ^{137}Cs remain at the site for the model to provide estimates. It is safe to say that the Tarbush site is highly variable with deposition and erosion occurring adjacent to each other. The high concentrations of ^{137}Cs in the soil crust would indicate that the parts of sites with high cover of biological soil crust have been stable for a long time.

Soils were collected from mesquite communities at four different locations from East to West across the Jornada Basin. Soil profiles were collected under the

Table 1
^{137}Cs concentration and estimated erosion rates calculated based on the profile distribution model (Walling and He, 2001) for the Jornada Experimental Range soil sampling sites

Number in Fig. 1	Vegetation site	$N(n)$	^{137}Cs ($Bq\,m^{-2}$) mean ± standard deviation	Coefficient of variation	Erosion ($t\,ha^{-1}\,year^{-1}$) mean	Comment
1	Tobosa-inside	3	2302.4 ± 463.8	20.1	5.9	Deposition
2	Tobosa-outside	3	2233.4 ± 200.6	9.0	5.6	Deposition
3	Tarbush	3(1)	1804.0 ± 2506.9	138.9	<2.8[a,b]	Deposition
4	Mesquite east	3	1228.3 ± 230.8	18.8	0.7	Deposition
4	Interdune-east	3(1)	498.3 ± 618.5	124.1	<−3.2[a]	Erosion
5	Mesquite-Geomet	6	3039.2 ± 1764.0	58.0	10.4	Deposition
5	Interdune-Geomet	5	527.0 ± 126.3	24.0	−4.1	Erosion
6	Mesquite-revegetation	6	705.8 ± 393.5	55.8	−3.0	Erosion
6	Interdune-revegetation	6(6)	0.0 ± 0.0	0	<−4.1[a]	Erosion
7	Mesquite-west	3(1)	646.2 ± 658.2	101.9	<−1.0[a]	Erosion
7	Interdune-west	3(1)	407.4 ± 377.4	92.6	<−3.3[a]	Erosion
8	Mayfield well exclosure	5	1112.0 ± 377.2	33.9	0.0	Reference
	All	49(10)	1184.2 ± 1266.6	107.0	1.5	Deposition

N is the number of samples per site, (n) is the number of samples per site where ^{137}Cs concentration was below detection levels ($<0.1\,Bq\,m^{-2}$).

[a] Vegetation type with at least one site where ^{137}Cs was below detection levels ($<0.1\,Bq\,m^{-2}$). The erosion rate for this vegetation is underestimated since we cannot calculate erosion rates when no ^{137}Cs is present. Estimates of erosion at the site with no ^{137}Cs are shown as $<-3.3\,t\,ha^{-1}\,year^{-1}$.

[b] The estimated erosion values for the Tarbush were +13.2, −1.6, and $<-3.3\,t\,ha^{-1}\,year^{-1}$.

mesquite canopy on the dunes and in the interspace between dunes. Concentration of ^{137}Cs was always greater under the mesquite canopy as compared with the interdune space indicating a net movement of soil into the mesquite dunes. However, there is a variation in the concentration of ^{137}Cs between sites. The Mesquite East site showed a net deposition (0.7 t ha^{-1} year^{-1}) under the mesquite canopy and a net soil loss in the interdune (<-3.2 t ha^{-1} year^{-1}) spaces. The Mesquite Geomet site showed high deposition (10.4 t ha^{-1} year^{-1}) under the mesquite canopy and net soil loss (-4.1 t ha^{-1} year^{-1}) in the interdune space. The Mesquite revegetation and the Mesquite west sites were both net soil loss sites under the mesquite canopy and in the interdune spaces. There was a great amount of variability at the mesquite vegetation sites. There does appear to be a net movement of soil resources from the interdune space to the mesquite dunes. This supports the hypotheses that shrublands increase the spatial and temporal heterogeneity of soil resources (Wright and Honea, 1986; Schlesinger et al., 1990). The variability among the mesquite sites indicates that soil movement is also occurring at the landscape scale, with higher ^{137}Cs concentrations at the east side of the Jornada basin than on the west side.

6. Conclusion

The data clearly show that ^{137}Cs can be effectively used to quantify soil redistribution at both plant-interspace and Jornada basin scales. The data confirm that significant plant-interspace scale soil redistribution occurs at mesquite dune vegetation with little ^{137}Cs found in the interdune spaces. In the Jornada basin soil fluxes are quite significant with an apparent west to east net movement of soil.

Acknowledgements

We would like to thank R.P. Gibbens and H.C. Monger for helpful discussions on the relationship between geomorphology, vegetation change, and soil movement and to Barbara Nolen for assistance with Fig. 1.

References

Belnap, J., Lange, O.L., 2001. Biological Soil Crusts: Structure, Function and Management. Springer, Berlin, p. 503.

Buffington, L.C., Herbel, C.H., 1965. Vegetational changes on a semidesert grassland range from 1858 to 1963. Ecological Monographs 35 (2), 139–164.

Bullock Jr., H.E., Neher, R.E., 1980. Soil Survey of Dona Ana County Area, New Mexico. USDA Soil Conservation Service, Washington, DC.

Cambray, R.S., Playford, K., Lewis, G.N.J., Carpenter, R.C., 1989. Radioactive fallout in air and rain: results to the end of 1988. AERE-R-13575, UK Atomic Energy Authority Report, Harwell, UK.

Carter, M.W., Moghissi, A.A., 1977. Three decades of nuclear testing. Health Physics 33, 55–71.

Cremers, A., Elsen, A., De Preter, P., Maes, A., 1988. Quantitative analysis of radiocaesium retention in soils. Nature 335, 247–249.
Gibbens, R.F., Tromble, J.M., Hennessey, J.T., Cardenas, M., 1983. Soil movement in mesquite duneslands and former grasslands of southern New Mexico from 1933 to 1980. Journal of Range Management 36, 145–148.
Gibbens, R.P., Beck, R.F., McNeely, R.P., Herbel, C.H., 1992. Recent rates of mesquite establishment in the northern Chihuahuan Desert. Journal of Range Management 45, 585–588.
Gile, L.H., Peterson, F.F., Grossman, R.B., 1966. Morphological and genetic sequences of carbonate accumulation in desert soils. Soil Science 101 (5), 347–360.
Gile, L.H., Hawley, J.W., Grossman, R.B., 1981. Soils and geomorphology in the basin and range area of southern New Mexico—guidebook to the Desert Project. New Mexico Bureau of Mines and Mineral Resources, Socorro, New Mexico.
Grover, H.D., Musick, H.B., 1990. Shrubland encroachment in southern New Mexico, USA: an analysis of desertification processes in the American southwest. Climatic Change 17, 305–330.
Havstad, K., Schlesinger, W., 1996. Reflections on a century of rangeland research in the Jornada Basin of New Mexico. In: Barrow, J.R., McArthur, E.D., Sosebee, R.E., Tausch., R.J. (Eds,), Proceedings Shrubland Ecosystem Dynamics in a Changing Environment, USDA Forest Service General Technical Report INT-GTR-338, pp. 10–15.
Hennessey, J.T., Gibbens, R.P., Tromble, J.M., Cardenas, M., 1983. Vegetation change from 1935 to 1980 in mesquite dunelands and former grassland of southern New Mexico. Journal of Range Management 36 (3), 370–374.
MacMahon, J.A., Wagner, F.H., 1985. The Mojave, Sonoran, and Chihuahuan deserts of North America. In: Evenari, M., Noy-Meir, I., Goodall, D.W. (Eds.), Hot Deserts and Shrublands. Ecosystems of the World. Elsevier Science, New York, pp. 105–202.
Playford, K., Toole, J., Adsley, I., 1993. Radioactive fallout in air and rain: results to the end of 1991. AEA-EE-0498, United Kingdom Atomic Energy Authority, Harwell, UK, pp. 30.
Ritchie, J.C., McHenry, J.R., 1990. Application of radioactive fallout cesium-137 for measuring soil erosion and sediment accumulation rates and patterns: a review. Journal of Environmental Quality 19, 215–233.
Ritchie, C.A., Ritchie, J.C., Plummer, G.L., 1971. Distribution of fallout cesium-137 in Cladonia mounds. The Bryologist 74, 359–362.
Schlesinger, W.H., Pilmanis, A.M., 1998. Plant-soil interactions in deserts. Biogeochemistry 42, 169–187.
Schlesinger, W.H., Reynolds, J.F., Cunningham, G.L., Huenneke, L.F., Jarrell, W.M., Virginia, R.A., Whitford, W.G., 1990. Biological feedbacks in global desertification. Science 247, 1043–1048.
Schlesinger, W.H., Raikes, J.A., Hartley, A.E., Cross, A.F., 1996. On the spatial patterns of soil nutrients in desert ecosystems. Ecology 77 (2), 364–374.
Sutherland, R.A., 1996. Caesium-137 soil sampling and inventory variability in reference samples; literature survey. Hydrological Processes 10, 34–54.
Tamura, T., 1964. Consequences of activity release: selective sorption reactions of cesium with soil minerals. Nuclear Safety 5, 262–268.
Wallbrink, P.J., Olley, J.M., Murray, A.S., 1994. Measuring soil movement using ^{137}Cs: implications of reference site variability. International Association of Hydrological Sciences Publication 224, 95–105.
Walling, D.E., He, Q., 1999. Improved models for estimating soil erosion rates from cesium-137 measurements. Journal of Environmental Quality 28, 611–622.
Walling, D.E., He, Q., 2001. Model for converting 137Cs measurements to estimates of soil redistribution on cultivated and uncultivated soils, and estimating bomb-derived ^{137}Cs reference inventory (Including Software for Model Implementation). A Contribution to the International Atomic Energy Agency Coordinated Research Programmes on Soil Erosion (D1.50.05) and Sedimentation (F3.10.01), Department of Geography, Exeter University, Exeter, UK.
Wright, R.A., Honea, J.H., 1986. Aspects of desertification in southern New Mexico, USA: soil properties of a mesquite duneland and a former grassland. Journal of Arid Environments 11, 139–145.